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Mathematical modeling of non-Newtonian fluid with chemical aspects: A new formulation and results by numerical technique

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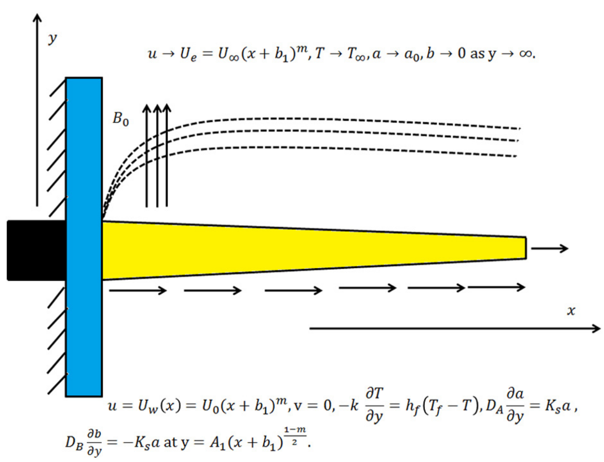
HIGHLIGHTS

- Stagnation point flow of Carreau fluid toward a variable sheet is investigated.
- Characteristics of homogeneous-heterogeneous reaction are explored.
- Convective condition for heat transfer is utilized.

GRAPHICAL ABSTRACT



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ABSTRACT

This work addresses the magnetohydrodynamic (MHD) stagnation point flow of Carreau fluid in presence of heterogeneous-homogeneous reactions. Flow is caused by nonlinearly stretching with variable sheet thickness and convective boundary condition. An electrically conducting fluid is considered in presence of non-uniform applied magnetic field. The governing equations of motion, energy and concentration are transformed into a set of nonlinear ordinary differential equations by utilizing the suitable transformations. Built-in Shooting technique is implemented to obtained the numerical solutions of resulting nonlinear systems. Characteristics of involved parameters on the velocity, temperature and concentration fields are plotted and examined. The skin friction coefficient and heat transfer at the surface are tabulated and analyzed for different physical parameters of interest.

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1. Introduction

Many heat and mass flow problem accompany the study of chemical reactions. The chemical reactions can either be homogeneous or heterogeneous. A homogeneous chemical process transpires uniformly right through a given phase while a heterogeneous chemical reaction occurs within the boundary of a phase. These reactions are distinguished in several processes like synthetic handling, sinewy protection hydrometallurgical industry, atmospheric flows, damage of crops because of freezing, production of ceramics and polymer, water and air pollutions, fog formation and dispersion, etc. The concept of chemical reaction is first time utilized by Merkin [1]. He examined the effect of homogeneous-heterogeneous reaction in viscous fluid flow over a stretched surface. His analysis shows that surface reaction dominates in the neighborhood of surface. Chaudhary and Merkin [2] discussed stretched flow of viscous liquid with heterogeneous and homogeneous. Krishnamurthy et al. [3] studied melting aspect in Williamson nanofluid flow with isothermal chemical process. Binary chemical reaction in flow of Maxwell fluid flow has been examined by Shafique et al. [4]. Hayat et al. [5] presented the usefulness of homogeneous/heterogeneous processes and melting heat characteristics in MHD flow toward stretched sheet with variable thickness. Shaw et al. [6] addressed effectiveness of heterogeneous and homogeneous processes in the flow of micropolar material induced by permeable stretched/shrinked sheet. Chemically reactive variable thermal conductivity stretched flow of Jeffrey material subject to stratifications is addressed by Hayat et al. [7]. Few recent attempts in this direction can be stated through refs. [8–12].

Researcher and scientists are still interested to disclose the characteristics of magnetohydrodynamics in the boundary layer region. It is due to its promising applications in various engineering and industrial processes. Such flow characteristics are interconnected in the design of cooling system with liquid metals, accelerators, MHD generators, nuclear reactor, pumps and flow meters and blood flow measurement. Having such feature in mind, the numerous researchers explore the behavior of magnetohydrodynamic flow for different flow configurations. Mukhopadhyay examined the effect of heat transfer and MHD aspects in flow by an exponentially stretching sheet embedded in a thermally stratified medium. Makinde [13] investigated the MHD flow due to moving surface subject to convective boundary condition. Heat transfer and MHD flow due to exponentially stretching sheet embedded in a thermally stratified medium is explored by Mukhopadhyay [14]. Laminar boundary layer flow and heat transfer with thermal radiation via the nonlinear is studied Rosseland approximation induced in a quiescent, electrically conducting viscoelastic fluid is studied by Cortell [15]. Wahed et al. [16] disclosed the hydromagnetic flow of nanofluid over a moving surface with variable thickness and non-linear velocity. The characteristics of MHD and heterogeneous and homogeneous reactions in stretched flow of viscoelastic fluid with melting heating is presented by Hayat et al. [17]. Few recent attempts in this direction can be stated through refs. [18–23].

Flow and heat transfer phenomena due to stretching surface has not lost its importance yet due to their variety widely occurrence in engineering and technological processes. Such process encountered in metal and polymer extrusion, glass fiber production, hot rolling, refrigeration, wire drawing, paper production, heat treated materials on a conveyor belt and heat conduction in tissues etc. Both the kinematics of heat transfer and stretching during such process has a decisive effect on the quality of the final products. Sakiadis [24] initiated the study of boundary layer flow over a stretching sheet moving with a constant speed. Crane [25] constructed closed form solution for the flow due to a linear stretching surface. Gupta [26] examined the heat and mass transfer analysis in flow over a stretching sheet. Afterwards many theoretical investigations have been carried out by numerous researchers Refs. [27–30].

It is noticed that flow due to the stretching sheet with variable thickness is not attended much. Thus the stretching sheet with variable thickness is more realistic in practical applications than a flat sheet. Such flow situation are of great use in mechanical, aeronautical, civil and marine structures. Variable thickness helps us to reduce the weight of structural elements and advance utilization of the material [31]. Thus Fang et al. [32] studied the boundary layer flow due to a stretching sheet with variable thickness. Thermal diffusive flow over a stretching sheet with variable thickness has been explored by Subhashini et al. [33]. The characteristics of Cattaneo-Christov heat flux in the flow of Maxwell fluid over a stretching surface with variable thickness is deliberated by Hayat et al. [34]. Stagnation point flow for melting heat transfer is examined by Hayat et al. [35]. Further Hayat et al. [36] worked on stretchable rotating disk with radiation in the presence of variable thickness. Non-Fourier heat flux for flow of Williamson liquid with variable thickness is considered by Salahuddin et al. [37]. Thermal diffusive flow over a stretched surface is analyzed by Subhashini et al. [38].

Main motivation in this study is to discuss stagnation point flow of non-Newtonian fluids toward a convectively heated sheet with variable thickness. Explicitly the objective of present study is as follows. Firstly to present modeling of problem using constitutive relations of Carreau fluid past a stretching sheet with variable thickness. Secondly to predict the Joule heating effect. Thirdly to examine homogeneous and heterogeneous reactions. Fourth to analyze the nonlinear stretching velocity. Heat transfer rate is discussed in the presence of convective boundary conditions. Also this communication describes heat transfer in absence of radiation and viscous dissipation. The resulting nonlinear coupled system are then solved by shooting method [39–41]. The discussion of plots and numerical computations is carried out for distinct physical parameters of interest.

2. Formulation

We consider the steady two-dimensional stagnation point flow of Carreau fluid toward a nonlinear stretching sheet with variable thickness. The fluid is electrically conducting. A non-uniform magnetic field $B_0(x+b_1)^{(m-1)/2}$ is applied transversely to the sheet [i.e. along the y-direction (see Fig. 1)]. The induced magnetic field is ignored, by considering small magnetic Reynolds number. The x- and y-axes are chosen along and normal to the stretching sheet. We assume that $U_w = U_0(x+b_1)^m$ and $U_e = U_\infty(x+b_1)^m$ are the velocities of sheet and external flow respectively (with U_0 and U_∞ as the corresponding reference velocities). Stretching sheet is taken at $y = A_1(x+b_1)^{(1-m)/2}$, where m represents the power index and A_1 relating very small constant so that the sheet is sufficiently thin. Note that for $m = 1$ our problem converts to a flat sheet. The temperature at the surface is a result of convective heating process which is represented by the coefficient of heat transport h_f and temperature of the hot fluid T_f. In addition the characteristics of homogeneous–heterogeneous reactions accounted. The homogeneous reaction for cubic autocatalysis is

$$A + 2B \rightarrow 3B, \quad \text{rate} = K_c a b^2, \tag{1}$$